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STABILITY LIMITS AND EFFICIENCY OF SWIRL-CAN COMBUSTOR MODULES BURNING NATURAL GAS FUEL

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16. Abstract

Individual swirl-can combustor modules burning natural gas fuel were evaluated for combustion efficiency, stability, and flame length. Tests were performed at ambient temperature and pressure with modules of various cone angles and a constant exit diameter of 2.25 in. (5.72 cm). Results showed a significant increase in combustion efficiency and stability, accompanied by a shorter flame length, for modules with wider cone angles. Decreasing the inlet orifice diameter from 0.75 to 0.60 in. (1.91 to 1.52 cm) increased combustion efficiency for all modules tested. The decrease in inlet orifice diameter had little effect on the general shape of a module's lean and rich blowout curves but did decrease the fuel-air ratio value at the point of maximum blowout velocity.

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SUMMARY

Individual swirl-can combustor modules for advanced turboject combustors using natural gas fuel were tested for combustion efficiency, stability, and flame length with natural gas fuel. Fuel and combustion air were at ambient temperature and pressure. Modules of various cone angles were tested. The module exit diameter and axial length from fuel tube to exit plane were held constant at 2.25 and 1.25 inches (5.72 and 3.18 cm, respectively). The effects of inlet orifice diameter and fuel tube diameter were also investigated.

Results showed a significant increase in combustion efficiency and stability, accompanied by a shorter flame length, for modules with wider cone angles. Decreasing the inlet orifice diameter from 0.75 to 0.60 inch (1.91 to 1.52 cm) increased combustion efficiency for all modules tested. The decrease in inlet orifice diameter had little effect on the general shape of a module's lean and rich blowout curves but did decrease the fuel-air ratio value at the point of maximum blowout velocity. A larger fuel-tube diameter had some detrimental effect on the stability limits of a swirl-can module.

INTRODUCTION

Recent studies have shown that liquefied natural gas (LNG) fuel offers significant advantages in some turbojet engine applications (refs. 1 and 2). Compared with conventional kerosene-type JP fuels, the much greater heat-sink capacity of LNG may make possible engine operation at higher turbine inlet temperatures. An alternative to higher turbine inlet temperatures would be to use the additional heat-sink capacity of LNG to maintain lower turbine metal temperatures and increase reliability and life. LNG also has a higher heat of combustion that would tend to lower specific fuel consumption.

The potential that LNG possesses as an aircraft fuel warrants study of the problems that might be involved in its use. One problem for any fuel is to maintain stable burning over the wide range of fuel-air ratios and operating conditions encountered in aircraft applications. Compared with JP fuels, LNG has much narrower flammability limits (ref. 3). Therefore, some difficulty may be expected in maintaining high combustion efficiency at severe operating conditions.

Actual operation of some advanced combustor designs based on previous limited work with gaseous fuels exhibited a decrease in combustion efficiency at low fuel-air ratios (ref. 4). The combustor designs reported in reference 4 consisted of arrays of swirl-can modules in a duct simulating a section of an annular turbojet combustion chamber. Each module acted as a combination carburetor and flame-holder. This design concept has several advantages over conventional combustor designs. The modules are uniformly distributed in the airstream to give a uniform combustor exit temperature profile and they can be individually throttled to improve the temperature profile. Also, from the standpoint of durability, the liner has no diluent-air entry holes so the usual areas of liner stress concentration and failure are eliminated.

Results from the work in reference 4 indicated poor ignition and flame propagation between swirl-can modules to be a problem. In addition, the combustor exit temperature profiles had hot spots downstream of the individual modules, possibly indicating long flame lengths.

To improve the performance of modular combustors, a study was undertaken to determine the effect of swirl-can module geometry on the stability and efficiency of individual modules. Single modules were tested in a closed duct at ambient conditions with natural gas. Stability and efficiency data were taken and visual observations of the flame were made.

TEST INSTALLATION

A 3.25-inch (8.25-cm) diameter test section housing the test module was connected to an air supply system (fig. 1). The module was supported in the duct by its fuel tube. The duct was designed so that the percent of blockage due to the test module would be comparable to that in present low-pressure-loss advanced turbojet modular-combustor designs (~45 percent).

Airflow rates were measured by a square-edged orifice installed according to ASME specifications. Fuel flows were measured by a turbine-type flowmeter. Twelve bare-wire Chromel-Alumel thermocouples (four at each of three centers of equal area, fig. 2) were used to measure the average temperature rise. The thermocouples were located 10 inches (25 cm) downstream of the swirl-can module exit to simulate the burning length of advanced combustor designs. A viewing window was located downstream of the test section. All tests were conducted with fuel and combustion air at ambient temperature and pressure.

TEST PROCEDURE

Stability data were taken by igniting the combustor module, setting the airflow to establish a reference velocity, and slowly varying the fuel flow until the combustor module blew out. The fuel-air ratio at blowout was calculated from the respective weight flows at blowout. Combustor reference velocity at blowout was calculated from the inlet-air temperature, airflow rate, the cross-sectional area of the duct, and atmospheric pressure.

Efficiency data were taken by maintaining constant the fuel-air ratio and reference velocity and measuring the combustor temperature rise. Combustion efficiency was defined as the ratio of actual temperature rise to theoretical temperature rise.

TEST COMBUSTORS

The operation of a typical swirl-can combustor module is illustrated schematically in figure 3. Fuel is injected from two simple orifices at near-sonic velocity near the walls of the module and normal to its axis. The tangential velocity of the fuel causes the fuel to spiral downstream along the walls of the module and mix rapidly with the air admitted through the inlet. Air, bypassing the module, mixes with the products of the primary combustion begun inside the module, recirculates just downstream of the module, and completes combustion.

Figure 4 shows the variations in swirl-can geometry that were tested. The initial test module (model A) was based on work done with hydrogen (ref. 5), propane (ref. 6), and natural gas (ref. 4). Reference 5 indicates that little change in stability, as measured by a peak blowout velocity parameter, was noted for variations in module length from 0.75 to 2.50 inches (1.91 to 6.35 cm) when burning hydrogen fuel. Also, little change in stability was noted by changing the inlet orifice diameter. In this program, modules of various cone angles were tested. The exit diameter of all modules except model A was 2.25 inches (5.72 cm). The exit diameter of the model A module was 2.00 inches (5.08 cm). The axial length from fuel tube to module exit was held constant at 1.25 inches (3.18 cm) for all modules. Models B1, C1, D1, and E1 had a 0.75-inch (1.91-cm) diameter inlet orifice, the same as model A. The diameter of the inlet orifice was decreased to 0.60 inch (1.21 cm) in models B2, C2, D2, and E2. Models F and G were tested with only a 0.60-inch (1.21-cm) orifice. The fuel tube was a nominal 0.25-inch (0.64-cm) diameter tube, with two 0.063-inch (0.160-cm) diameter fuel injection holes. Although no significant effect due to fuel injection velocity was expected, the fuel injection holes were sized for sonic velocity at most conditions. To observe the effect of fuel-tube diameter on stability, model F was also tested with a nominal 0.5-inch (1.25-cm) diameter fuel tube (model F1).

A typical chemical analysis of the natural gas used in these tests is shown in table I.

RESULTS AND DISCUSSION

The combustion stability limits and efficiency data of the model A test module are shown in figure 5. Visual observation of the flame revealed moderately long flame lengths (~8 in. (20 cm)) for rich fuel-air ratios at reference velocities below 90 feet per second (27.4 m/sec). Above this velocity, the visual flame appeared to get shorter with increasing reference velocity. Combustion efficiency was best when the module operated in the lean portion of the stability curve but was considerably less than was anticipated.

The stability and efficiency data for models B1, C1, D1, and E1 are shown in figures 6(a) to (d). Similar data for models B2, C2, D2, E2, F, and G are shown in figures 6(e) to (j). In some cases (e.g., fig. 6(j)), the point of maximum blowout reference velocity could not be determined accurately from the data obtained. The sensitivity of fuel and air controls made it difficult to maintain a desired fuel-air ratio while simultaneously increasing the velocity above the values for which data are presented. In such cases, the maximum blowout reference velocity was taken, for comparisons that follow, to be the largest velocity for which a data point with stable burning was actually obtained.

The results show variations in combustion stability and efficiency with module cone angle and inlet orifice diameter. A discussion of these variations is presented in the next section.

Efficiency

Inasmuch as these tests were performed at relatively severe combustion conditions (air and fuel at ambient temperature and pressure), the absolute values of efficiency are not as significant as the trends in efficiency noted with all the modules.

Combustion efficiency was most noticeably affected by the change in inlet orifice diameter. In general, the efficiency substantially increased for models B to E when the smaller (0.60 inch (1.21 cm)) diameter orifice was used.

In general, for both values of inlet orifice diameter, combustion efficiency was lowest for the shallowest angle module (model B) and gradually increased with increasing module angle. The low efficiency of the shallow angle modules at the 90-foot-per-second (27-m/sec) reference velocity and high fuel-air ratios was due partly to the long flame lengths of these modules extending beyond the thermocouple plane. The model B1 module exhibited flame lengths over 10 inches (25 cm) long at velocities below 120 feet per second (36.6 m/sec). The flame lengths were noticeably shorter for the wider angle modules. In figure 7, the arithmetic averages of all three combustion efficiencies measured at a constant reference velocity are plotted against the conic half-angle of the module. This figure shows an increasing trend in efficiency with module angle. The trend may be attributed to two factors:

(1) Increasing the module angle increases the angle at which the exhaust gases along the lip of the module penetrate the bypass airstream causing greater mixing.

(2) The recirculation back into the module is increased with increasing module angle due to the greater divergence of the swirling mixture inside the module.

Maximum Blowout Velocity

As shown in figure 8, the maximum blowout velocity attained by the swirl-can modules increased with increasing module angle, thus following the same trend noted for combustion efficiency. However, the maximum reference velocity for a particular module was not noticeably affected by the use of a smaller inlet orifice, which is not the same trend observed for the combustion efficiency. The lack of an inlet-orifice-size effect on stability (as measured by a peak-blowout-velocity parameter) was also noticed in the work done with hydrogen in reference 5.

Stability Limits

Effect of reference velocity. - The lean stability limits of the swirl-can modules were not strongly affected by reference velocity. Each modul exhibited a nearly constant value of fuel-air ratio at lean blowout.

The rich stability limits for the shallow angle swirl-can modules were strongly affected by velocity. As previously stated, the shallowest angle modules exhibited flame lengths over 10 inches (25 cm) long at high fuel-air ratios and velocities below 120 feet per second (36.6 m/sec). The effect of velocity on the rich blowout limits of the various modules decreased as the module angle was increased. With the widest angle module, the variation of rich blowout limit with reference velocity was slight (fig. 6(j)).

Effect of inlet orifice diameter and cone angle. - By increasing the inlet orifice diameter, more air is allowed directly into the primary zone and, therefore, more fuel is required to maintain combustion. As would be expected, the fuel-air ratio at the point of maximum blowout velocity is higher for the modules with the 0.75-inch (1.91-cm) diameter inlets than for the modules with the 0.60-inch (1.52-cm) diameter inlets, as shown in figure 9. (In cases where the fuel-air ratio at the maximum blowout reference velocity could not be determined uniquely from the data obtained, a value was selected midway between the two values at which the highest velocities were achieved.) Figure 9 also shows that for the same inlet orifice size, the fuel-air ratio at the point of maximum blowout velocity increases with increasing cone angle. The lean and rich blowout limit curves also follow these trends. Figure 10 shows the effects of inlet orifice diameter and cone angle on lean blowout for a reference velocity of 160 feet per second (48.8 m/sec). The increase in fuel-air ratio necessary to maintain combustion with the wider angle modules indicates that more bypass air recirculates into the primary and secondary zones of combustion for the wider angle modules.

The shape of the rich side of the stability curves, the efficiency, and the flame lengths all indicate that the shallow angle modules do not provide sufficient mixing of the primary products of combustion with the bypass airstream and therefore combustion is not completed in the secondary zone.

Effect of fuel-tube size. - Stability data were taken for the model F1 module and are shown in figure 11. The decrease in stability is attributed to partial destruction of the vortex flow near the fuel tube and an increase in inlet-air velocity around the fuel tube due to the decrease in cross-sectional area there.

Applications

The widest angle test module with the smaller inlet diameter (model G) appears to be the most desirable for a modular array combustor application. It has a short flame length, high efficiency, and good stability at high reference velocities. Further improvement might be achieved with modules of even wider angles than 30°. Such modules would require smaller inlet diameters or shorter lengths from fuel tube to exit plane.

The narrower stability limits of the widest angle module at the lower reference velocities are not expected to be a problem in designing a combustor. No rich blowout of an array of model A type modules has been experienced at rich operating conditions where the rich stability limit for that module indicates blowout should occur (ref. 4). This is attributed to a high degree of interaction between modules at high fuel-air ratios. At low fuel-air ratios, the flame is confined to the module and the degree of interaction is less. Lean blowout, good efficiency at lean fuel-air ratios, and stability at high reference velocities are therefore the most important criteria in selecting the best module design to be used in an array for a combustor.

The inlet-air temperature and pressure conditions for combustion in supersonic aircraft engines will usually be much higher than the severe ambient conditions under which these tests were performed. Therefore some widening of the stability limits for combustion in aircraft engines can be expected. The magnitude of the effects of temperature and pressure were not investigated.

Complexity of a combustor design could be reduced if a larger fuel tube (i.e., 0.50 in. (1.27 cm)) were used both to supply fuel to the modules and to support them in the combustion chamber. The adverse effect on stability limits observed with the larger fuel tube was not of such a magnitude as to eliminate further consideration of its use in a modular array design. The effect of a larger fuel tube would not be as important if the module size were correspondingly increased.

SUMMARY OF RESULTS

Individual swirl-can combustor modules were tested at ambient temperature and pressure with natural gas fuel. Stability and efficiency data were taken, as well as visual observations of flame lengths. The exit diameter and axial length from fuel tube to exit plane of the module were held constant. The following trends in performance were found:

1. The efficiency and maximum blowout velocity both increased with increasing module cone angle.
2. The efficiency increased when the inlet orifice diameter was decreased from 0.75 to 0.60 inch (1.91 to 1.52 cm).
3. The general shape of the stability curve did not change when the inlet orifice diameter was decreased; but the value of fuel-air ratio at the point of maximum blowout velocity and the lean and rich limits did decrease.
4. A larger fuel-tube diameter had some detrimental effect on the stability limits of a swirl-can module.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 14, 1970,
720-03.

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TABLE I. - PROPERTIES OF NATURAL GAS

Chemical properties of natural gas, percent by volume:	
CH_4	94.2
N_2	1.06
He	0.04
CO_2	0.93
C_2H_6	3.1
C_3H_8	0.43
C_4H_{10} and C_5H_{12}	0.34
O_2	0.02
Molecular weight	17.1493
Density (30 in. of H_2O, 60° F), lb/ft^3 (kg/m^3)	0.04541 (0.7274)
Lower heat of combustion, Btu/lb (J/g)	20 531 (47 793)
Hydrogen-carbon ratio	0.3273
Heat of formation, Btu/lb(J/g)	-1855 (-4318)
Percent inert gas by weight	4.16

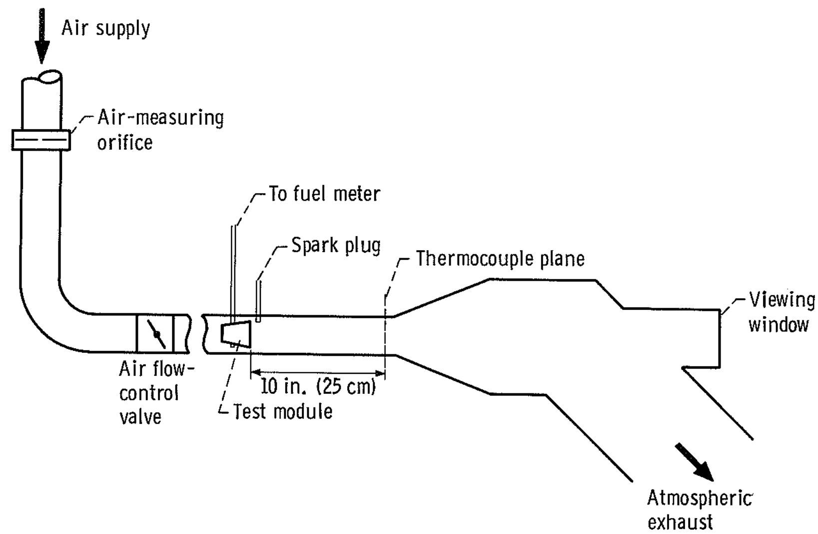


Figure 1. - Schematic of test installation.

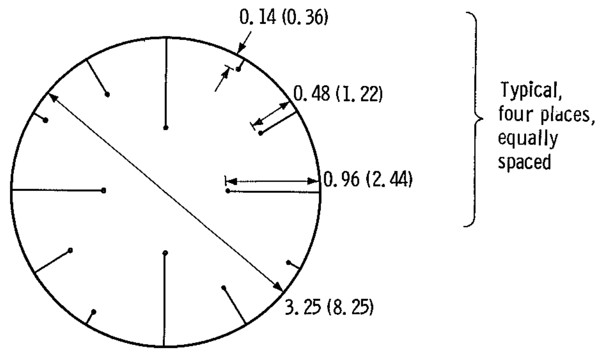


Figure 2. - Thermocouple plane (looking upstream). (Dimensions are in inches (cm).)

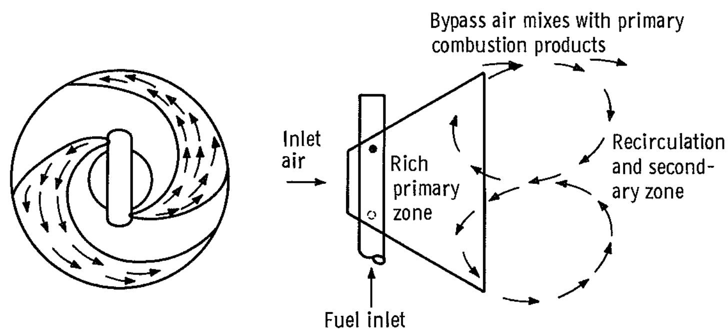
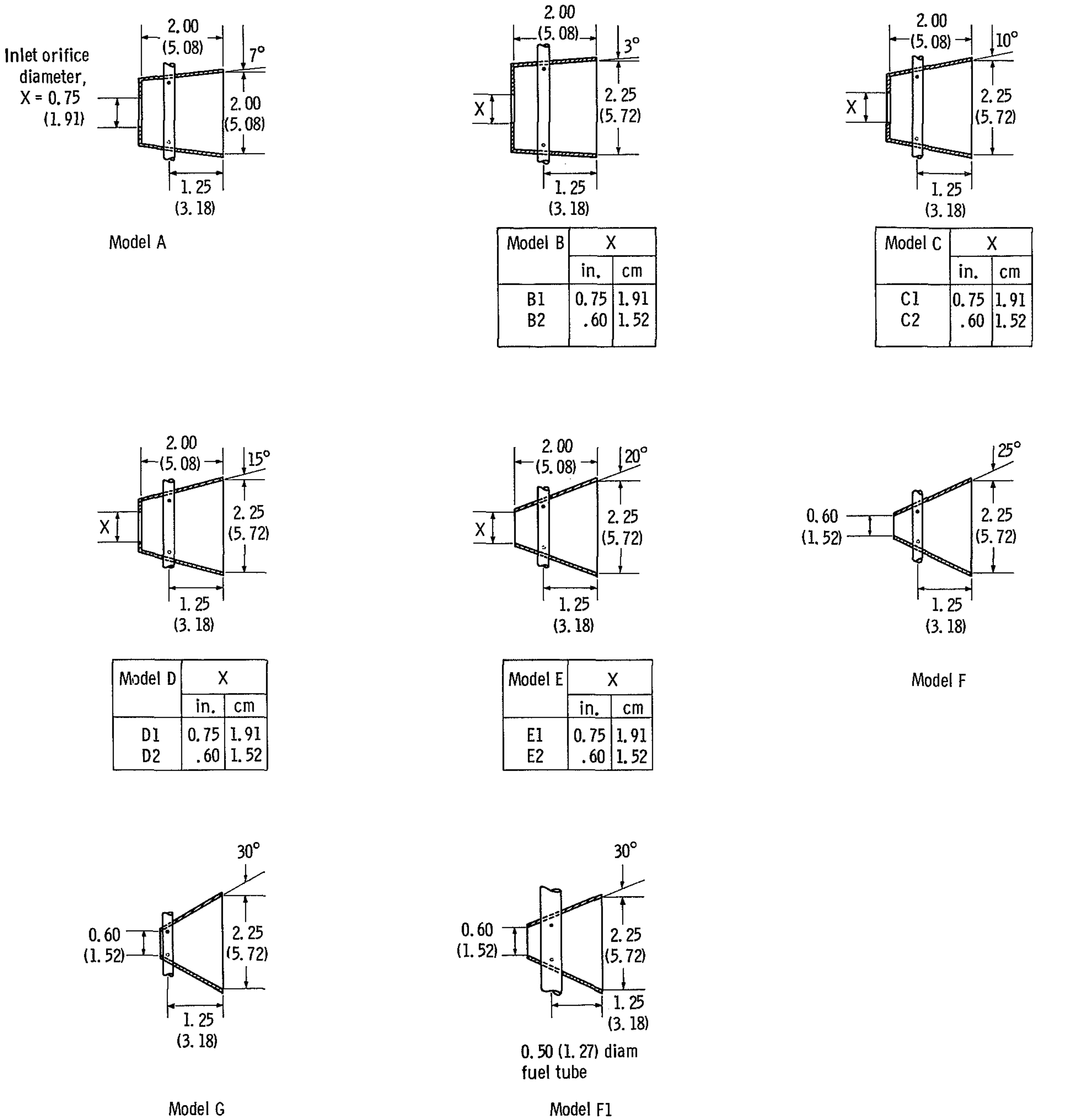


Figure 3. - Operation of typical swirl-can combustor module.



Model B	X	
	in.	cm
B1	0.75	1.91
B2	.60	1.52

Model C	X	
	in.	cm
C1	0.75	1.91
C2	.60	1.52

Model D	X	
	in.	cm
D1	0.75	1.91
D2	.60	1.52

Model E	X	
	in.	cm
E1	0.75	1.91
E2	.60	1.52

Figure 4. - Swirl-can test modules. Fuel injection holes, 0.063 inch (0.160 cm) in diameter. Fuel-tube diameter (except for model F1), 0.25 inch (0.64 cm). (Dimensions are in inches (cm).)

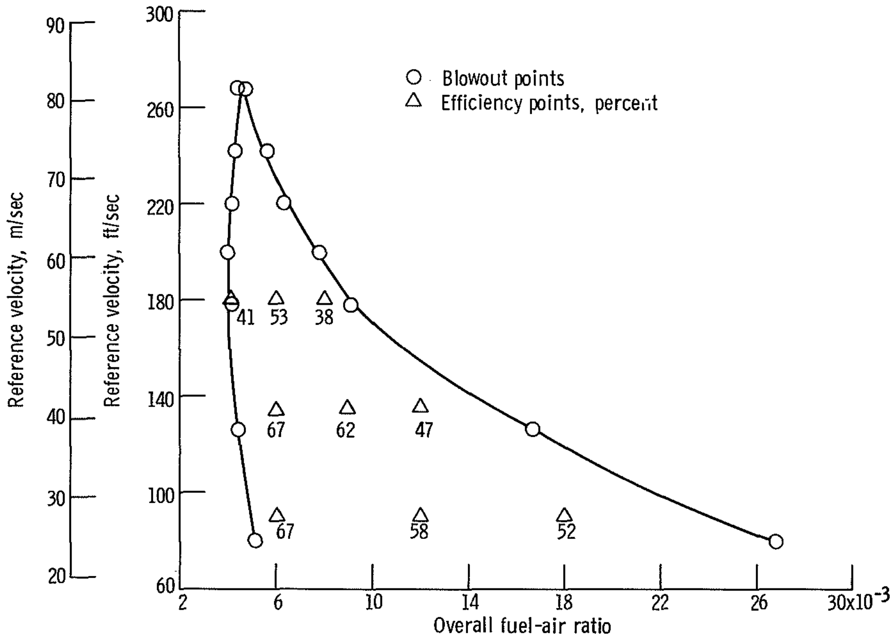


Figure 5. - Stability and efficiency of model A combustor module.

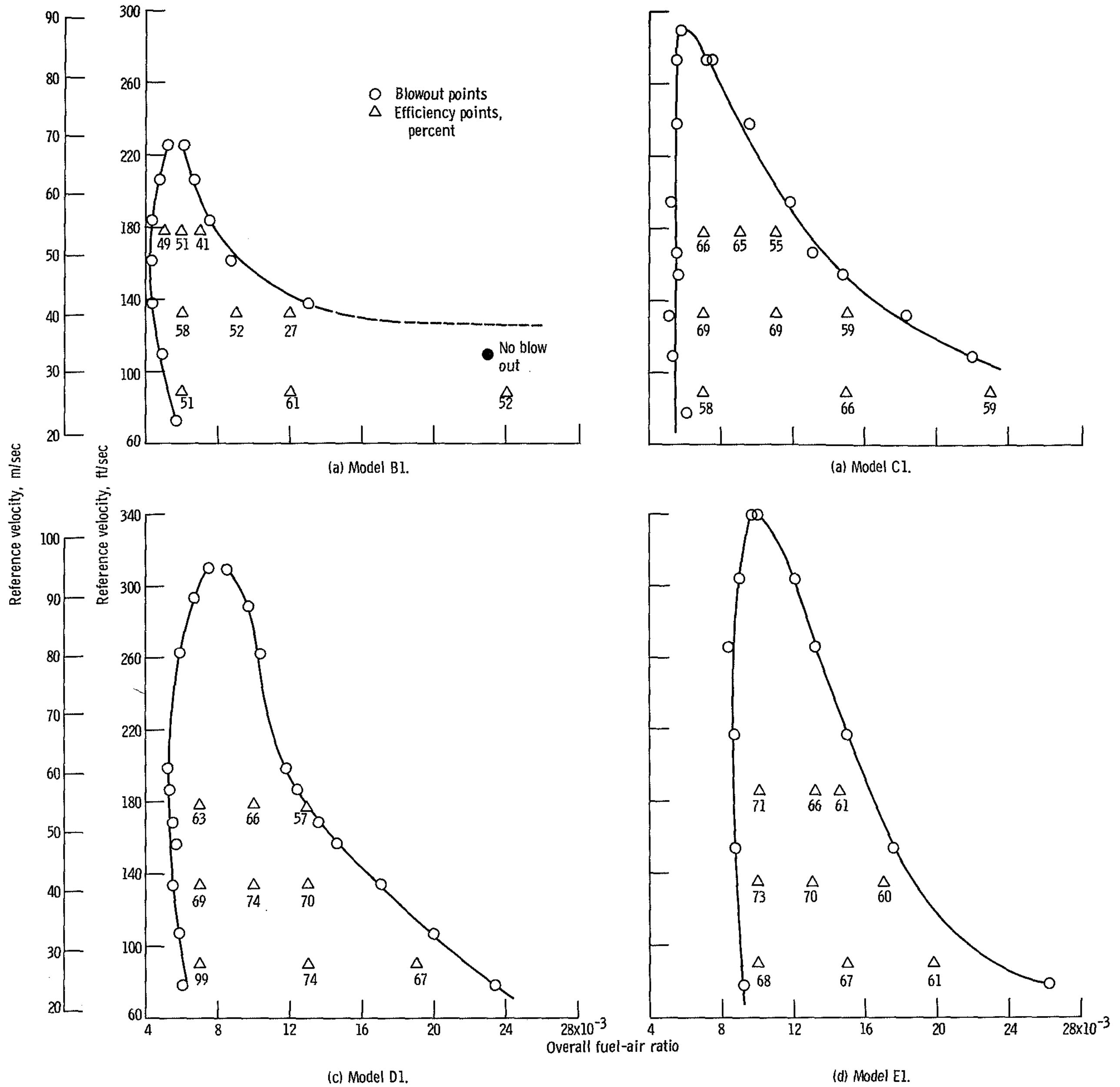


Figure 6. - Stability and efficiency for various combustor modules.

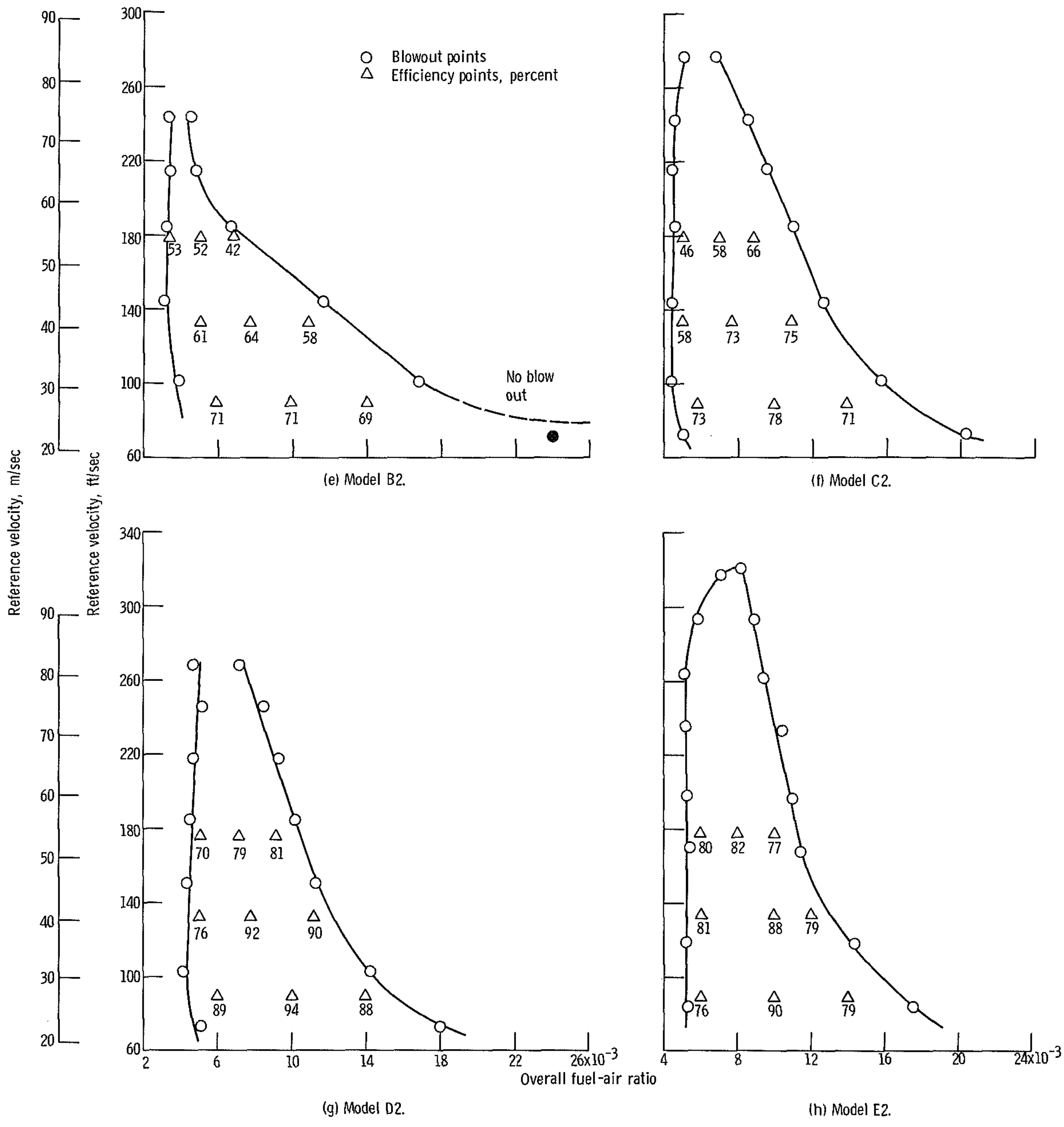
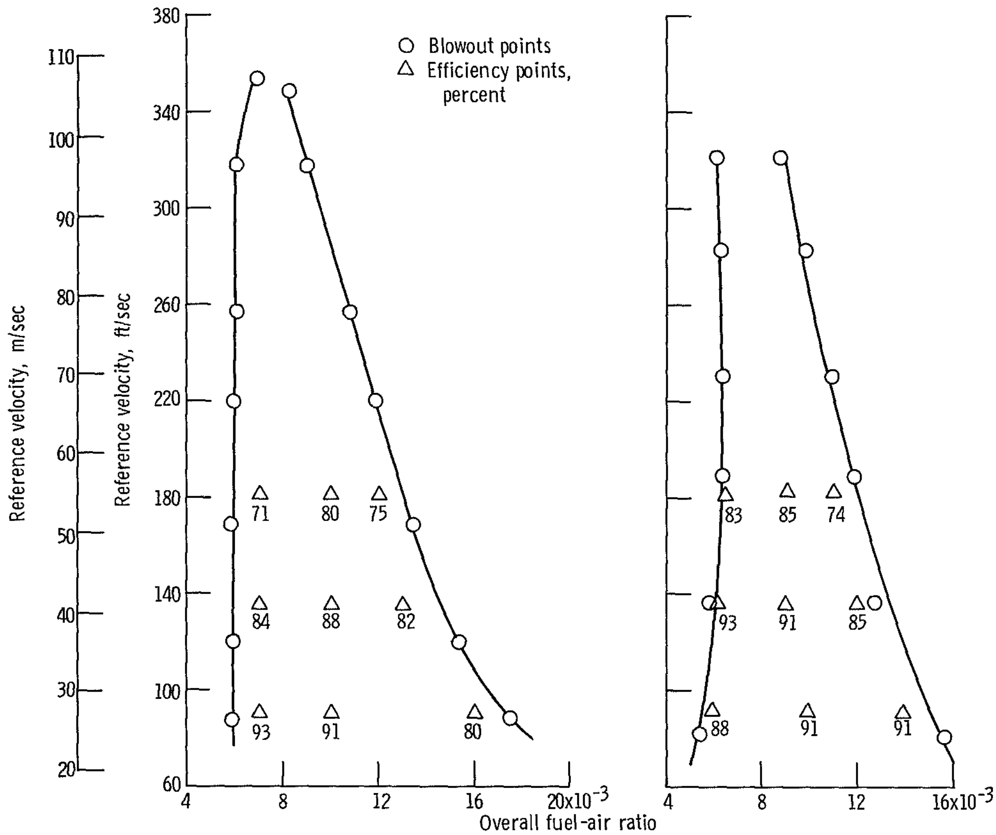


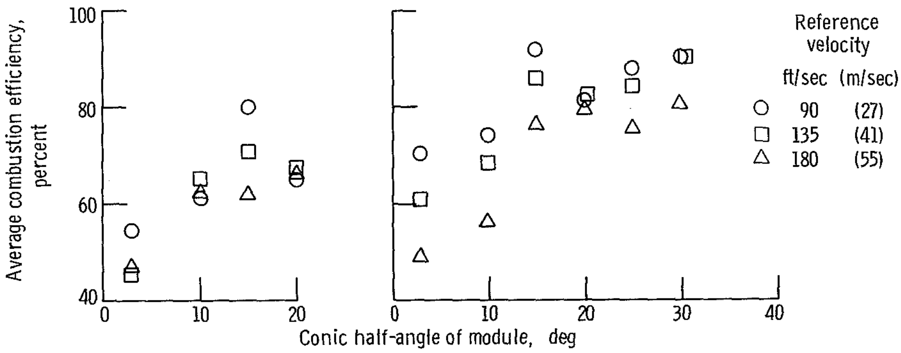
Figure 6. - Continued.



(i) Model F.

(j) Model G.

Figure 6. - Concluded.



(a) Inlet diameter, 0.75 inch (1.91 cm).

(b) Inlet diameter, 0.60 inch (1.52 cm).

Figure 7. - Effect of cone angle on combustion efficiency.

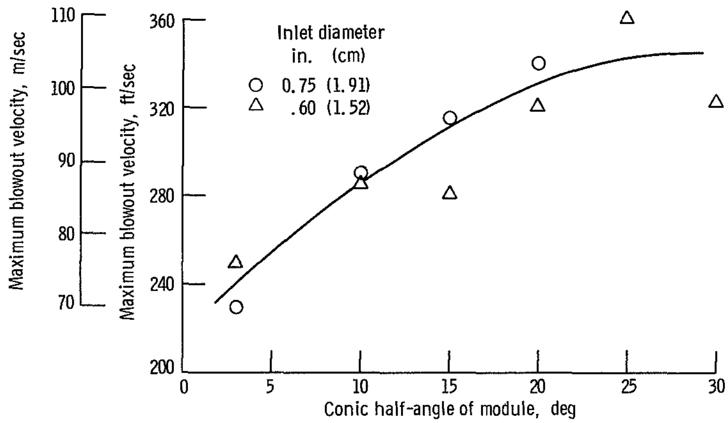


Figure 8. - Effect of module half-angle on maximum blowout velocity.

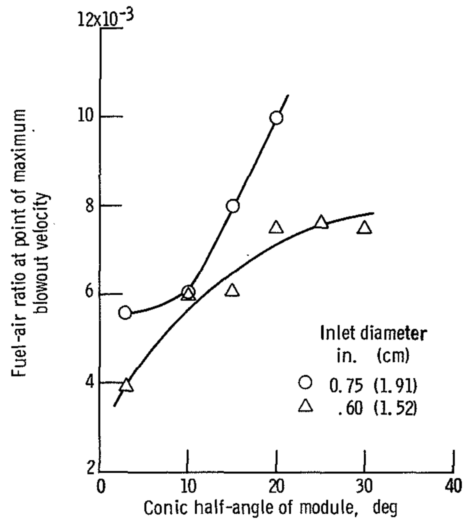


Figure 9. - Effect of inlet orifice diameter and module half-angle on fuel-air ratio at point of maximum blowout velocity.

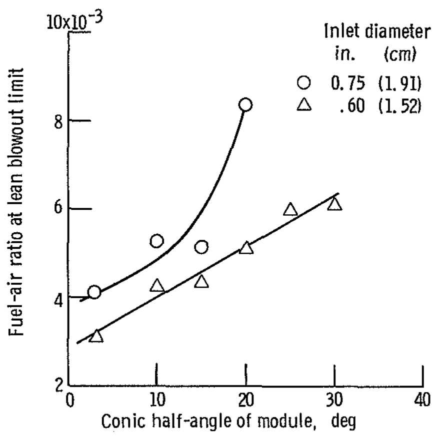


Figure 10. - Effect of inlet orifice diameter and module half-angle on fuel-air ratio at lean blowout. (Reference velocity, 160 ft/sec (48.8 m/sec).)

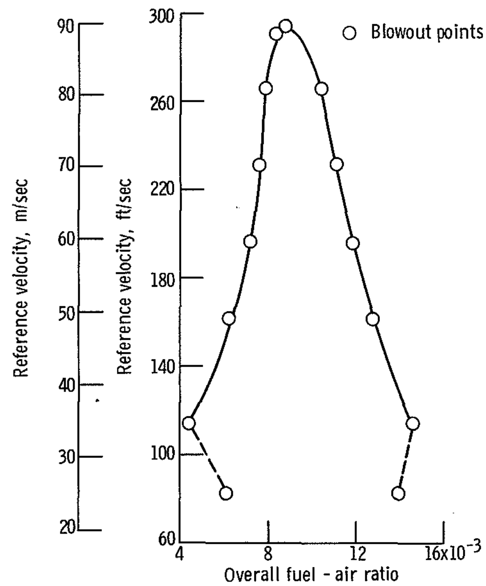


Figure 11. - Stability data for model F1 combustor module.

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